

ON UNIQUELY π -CLEAN RINGS

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Abstract: An element of a ring is unique clean if it can be uniquely written as the sum of an idempotent and a unit. A ring R is uniquely π -clean if some power of every element in R is uniquely clean. In this article, we prove that a ring R is uniquely π -clean if and only if for any $a \in R$, there exists an $m \in \mathbb{N}$ and a central idempotent $e \in R$ such that $a^m - e \in J(R)$, if and only if R is abelian; every idempotent lifts modulo $J(R)$; and R/P is torsion for all prime ideals P containing the Jacobson radical $J(R)$. Further, we prove that a ring R is uniquely π -clean and $J(R)$ is nil if and only if R is an abelian periodic ring, if and only if for any $a \in R$, there exists some $m \in \mathbb{N}$ and a unique idempotent $e \in R$ such that $a^m - e \in P(R)$, where $P(R)$ is the prime radical of R .

MR(2010) Subject Classification: 16U99, 16E50.

1. INTRODUCTION

An element of a ring is unique clean if it can be uniquely written as the sum of an idempotent and a unit. A ring R is uniquely clean if every element in R is uniquely clean. Many results on such rings can be found in [2], [4] and [10]. Following Zhou [10], a ring R is uniquely π -clean if some power of every element in R is uniquely clean. This is a natural generalization of uniquely clean rings. Some structures of such rings was claimed in [10]. The motivation of this paper is to develop further characterizations of uniquely π -clean rings.

In Section 2, we investigate the structure theorems of uniquely π -clean rings, and prove that a ring R is uniquely π -clean if and only if for any $a \in R$, there exists an $m \in \mathbb{N}$ and a central idempotent $e \in R$ such that $a^m - e \in J(R)$, if and only if for any $a \in R$, there exists an $m \in \mathbb{N}$ and a unique $e \in R$ such that $a^m - e \in J(R)$, and $J(R) = \{x \in R \mid x^m - 1 \in U(R) \text{ for all } m \in \mathbb{N}\}$. An exchange-like characterization of such rings are also obtained. In Section 3, we characterize uniquely π -cleanness by means of some prime ideals. It is shown that a ring R is strongly π -clean if and only if R is abelian; every idempotent lifts modulo $J(R)$; and R/P is torsion for all prime ideals P containing the Jacobson radical $J(R)$. Furthermore, we consider a type of radical-like ideal $J^*(R)$, and characterize uniquely π -clean ring R by using such special one. A ring R is periodic if for any $a \in R$ there exist distinct $m, n \in \mathbb{N}$ such that $a^m = a^n$. In the last section, we investigate uniquely π -clean

ring with nil Jacobson radical. We prove that a ring R is uniquely π -clean and $J(R)$ is nil if and only if R is an abelian periodic ring, if and only if for any $a \in R$ there exists some $m \in \mathbb{N}$ such that $a^m \in R$ is uniquely nil clean, if and only if for any $a \in R$, there exists some $m \in \mathbb{N}$ and a unique idempotent $e \in R$ such that $a^m - e \in P(R)$, where $P(R)$ is the prime radical of R . Here, an element $a \in R$ is uniquely nil clean if there exists a unique idempotent $e \in R$ such that $a - e \in R$ is nilpotent ([2] and [4]).

Throughout, all rings are associative with an identity. We use $J(R)$ and $P(R)$ to denote the the Jacobson radical and prime radical of a ring R . $N(R)$ stands for the set of all nilpotent elements in R .

2. STRUCTURE THEOREMS

The aim of this is to explore the structures of uniquely π -clean rings. Recall that a ring R is an exchange ring if for any $a \in R$ there exists an idempotent $e \in aR$ such that $1 - e \in (1 - a)R$. A ring R is an exchange ring if and only if, for every right R -module A and any two decompositions $A = M \oplus N = \bigoplus_{i \in I} A_i$, where $M_R \cong R$ and the index set I is finite, there exist submodules $A'_i \subseteq A_i$ such that $A = M \oplus (\bigoplus_{i \in I} A'_i)$. The class of exchange rings is very large. For instances, regular rings, π -regular rings, strongly π -regular rings, semiperfect rings, left or right continuous rings, clean rings and unit C^* -algebras of real rank zero, etc. We begin with

Lemma 2.1. *Every uniquely π -clean ring is an abelian exchange ring.*

Proof. Let R be uniquely π -clean, let $e \in R$ be an idempotent, and let $r \in R$. Choose $x = 1 - (e + er(1 - e))$. Then there exists some $n \in \mathbb{N}$ such that $x^n \in R$ is uniquely clean. One easily checks that $x^n = x = e + (1 - 2e - er(1 - e)) = (e + er(1 - e)) + (1 - 2(e + er(1 - e)))$. Further, $e = e^2 \in R$, $(1 - 2e + er(1 - e))^{-1} = (1 - er(1 - e))(1 - 2e)$, $(e + er(1 - e)) = (e + er(1 - e))^2$ and $(1 - 2(e + er(1 - e)))^2 = 1$. By the uniqueness, we get $e = e + er(1 - e)$, and then $er = ere$. Likewise, $re = ere$. Thus, $er = re$, and therefore R is abelian.

For any $a \in R$, then we can find some $m \in \mathbb{N}$ such that $a^m \in R$ is clean. Write $a^m = f + v$, where $f = f^2, v \in U(R)$. Then $a^m - f^m = v$, and so $a - f \in U(R)$. This implies that R is strongly clean. In view of [9, Theorem 30.2], R is an exchange ring. \square

A ring R is strongly clean if for any $a \in R$ there exists an idempotent $e \in R$ such that $a - e \in U(R)$ and $ea = ae$. As a consequence of Lemma 2.1, every uniquely π -clean ring is strongly clean. A ring R is uniquely clean provided that every element in R can be uniquely written as the sum of an idempotent and a unit. It is easy to verify that $\mathbb{Z}/3\mathbb{Z}$ is not uniquely clean as $2 = 0 + 2 = 1 + 1$, while $\mathbb{Z}/3\mathbb{Z}$ is uniquely π -clean. Let $R = \bigoplus_{p \text{ is prime}} \mathbb{Z}/(p+1)\mathbb{Z}$.

Then R is strongly clean. For any $1 \leq m \leq [\log_2 p]$, $2^m \in \mathbb{Z}/(p+1)\mathbb{Z}$ is not uniquely clean. Thus, R is not uniquely π -clean. Therefore, we conclude that $\{\text{uniquely clean rings}\} \subsetneq \{\text{uniquely } \pi\text{-clean rings}\} \subsetneq \{\text{strongly clean rings}\}$.

Theorem 2.2. *Let R be a ring. Then R is uniquely π -clean if and only if*

- (1) R is abelian;
- (2) Every idempotent lifts modulo $J(R)$;

(3) $R/J(R)$ is uniquely π -clean.

Proof. Suppose R is uniquely π -clean. In view of Lemma 2.1, R is an abelian exchange ring. This proves (1) and (2), in terms of [9, Theorem 30.2]. For any $\bar{a} \in R/J(R)$, then $a \in R$ is uniquely π -clean. Thus, we have some $n \in \mathbb{N}$ such that $a^n \in R$ is uniquely clean. This implies that $a^n = e + u, e = e^2 \in R, u \in U(R)$. Hence, $\bar{a}^n = \bar{e} + \bar{u}$. Write $\bar{a}^n = \bar{f} + \bar{v}, \bar{f} = \bar{f}^2 \in R/J(R), \bar{v} \in U(R/J(R))$. Clearly, every unit lifts modulo $J(R)$. So we may assume that $f = f^2 \in R, v \in U(R)$. As a result, there exists some $r \in J(R)$ such that $a^n = e + u = f + (v + r)$. By the uniqueness, we get $e = f$. Therefore $R/J(R)$ is uniquely π -clean.

Conversely, assume that (1) – (3) hold. For any $a \in R$, we have $\bar{a} \in R/J(R)$, and so there exists some $n \in \mathbb{N}$ such that $\bar{a}^n \in R/J(R)$ is uniquely clean. By hypothesis, idempotents lift modulo $J(R)$. In addition, units lift modulo $J(R)$. Thus, $a^n = e + u, e = e^2 \in R, u \in U(R)$. Write $a^n = f + v, f = f^2, v \in U(R)$. Then $\bar{a}^n = \bar{f} + \bar{v}$. By the uniqueness, we get $\bar{e} = \bar{f}$, i.e., $e - f \in J(R)$. This infers that $f(1 - e) = (e - f)(e - 1) \in J(R)$. As every idempotent in R is central, $f(1 - e) \in R$ is an idempotent, thus, $f(1 - e) = 0$. It follows that $f = fe$. Likewise, $e = ef$. Consequently, $e = f$, and therefore R is uniquely π -clean. \square

Corollary 2.3. *Every corner of a uniquely π -clean ring is uniquely π -clean.*

Proof. Let R be uniquely π -clean, and let $e = e^2 \in R$. In light of Theorem 2.2, $e \in R$ central. For any $eae \in eRe$, then $eae + 1 - e \in R$ is uniquely π -clean. So we have some $n \in \mathbb{N}$ such that $(eae + 1 - e)^n \in R$ is uniquely clean. Thus, $(eae + 1 - e)^n = f + u, f = f^2 \in R, u \in U(R)$, and so $(eae)^n = efe + eue$ is clean in eRe . Write $(eae)^n = g + v, g = g^2 \in eRe, v \in U(eRe)$. Then $(eae + 1 - e)^n = (eae)^n + 1 - e = g + (v + 1 - e)$, where $g = g^2 \in R, v + 1 - e \in U(R)$. Thus, $g = f = ege = efe$, as required. \square

Lemma 2.1 shows that every uniquely π -clean ring is an abelian exchange ring. We next exhibit an exchange-like property of such rings.

Theorem 2.4. *Let R be a ring. Then R is uniquely π -clean if and only if*

- (1) R is abelian;
- (2) For any $a \in R$, there exists an $n \in \mathbb{N}$ and a unique idempotent $e \in a^n R$ such that $1 - e \in (1 - a^n)R$.

Proof. Suppose that R is uniquely π -clean. In view of Lemma 2.1, every idempotent in R is central. For any $a \in R$, there exists some $n \in \mathbb{N}$ such that $a^n \in R$ is uniquely clean. Write $a^n = f + v$, where $f = f^2, v \in U(R)$. Set $g = v(1 - f)v^{-1}$. Then $g = g^2 \in R$. Obviously, we get

$$\begin{aligned} (a^n - g)v &= (f + v - v(1 - f)v^{-1})v \\ &= v^2 + fv - v + vf \\ &= a^{2n} - a^n. \end{aligned}$$

Thus $g - a^n \in (a^n - a^{2n})R$, and so $g \in a^n R$ and $1 - g \in (1 - a^n)R$.

If there exists an idempotent $h \in a^n R$ such that $h \in a^n R$ and $1 - h \in (1 - a^n)R$. Write $h = a^n x, xh = x$. Then $xa^n x = x$. It is easy to verify that $xa^n = x(a^n x)a^n = a^n x(xa^n) = a^n(xa^n)x = a^n x$. Write $1 - h = (1 - a^n)y, y(1 - h) = y$. Likewise, $y(1 - a^n) = (1 - a^n)y$. One directly checks that $(a^n - (1 - h))^{-1} = x - y$, i.e., $a^n - (1 - h) \in U(R)$. By the uniqueness, we get $1 - h = f$. Hence, $g = v(1 - f)v^{-1} = 1 - f = h$, as desired.

Conversely, assume that (1) and (2) hold. For any $a \in R$, there exists an $n \in \mathbb{N}$ and a unique idempotent $e \in a^n R$ such that $1 - e \in (1 - a^n)R$. As in the preceding discussion, we

get $a^n - (1 - e) \in U(R)$. Write $a^n = f + v$, where $f = f^2, v \in U(R)$. Set $g = v(1 - f)v^{-1}$. Then $g = g^2 \in R$. Further, we have $g \in a^n R$ and $1 - g \in (1 - a^n)R$. By the uniqueness, we obtain $g = e$, and so $v(1 - f)v^{-1} = e$. Thus, $f = 1 - e$, hence the result. \square

Corollary 2.5. *Let R be a ring. Then R is uniquely π -clean if and only if*

- (1) *Every idempotent in R is central.*
- (2) *For any $a \in R$, there exists an $n \in \mathbb{N}$ and a unique idempotent $e \in Ra^n$ such that $1 - e \in R(1 - a^n)$.*

Proof. Obviously, a ring R is uniquely π -clean if and only if so is the opposite ring R^{op} . Applying Theorem 2.4 to R^{op} , we complete the proof. \square

A ring R is local if it has only one maximal right ideal. A ring R is potent if for any $a \in R$ there exists some $n \in \mathbb{N}$ such that $a^n = a$. We note that every potent ring is commutative.

Lemma 2.6. *Let R be a local ring. If R is uniquely π -clean, then $R/J(R)$ is potent.*

Proof. Suppose that there exists some $a \in R$ such that $a^n - a \notin J(R)$ for all $n \geq 2$. Then $a(a^{n-1} - 1) \in U(R)$ as R is a local ring. This implies that $a \in U(R)$ and $a^{n-1} - 1 \in U(R)$ for all $n \geq 2$. Since R is uniquely π -clean, we have an $m \in \mathbb{N}$ such that $a^m \in R$ is uniquely clean. But $a^m = 0 + a^m = 1 + (a^m - 1)$, a contradiction. Therefore, for any $a \in R$, there exists some integer $n \geq 2$ such that $a^n - a \in J(R)$. That is, $R/J(R)$ is potent. \square

The following lemma was firstly claimed by Lee and Zhou [11] without proof. Here, we include an alternative proof for the self-contained.

Lemma 2.7. *Let R be a ring. Then R is uniquely π -clean if and only if*

- (1) *R is abelian;*
- (2) *Every idempotent lifts modulo $J(R)$;*
- (3) *$R/J(R)$ is potent.*

Proof. Suppose that R is uniquely π -clean. In view of Theorem 2.2, $R/J(R)$ is uniquely π -clean, idempotents lift modulo $J(R)$ and idempotents in R are central. Clearly, $R/J(R)$ is isomorphic to a direct product of some primitive rings R_i . Thus, R_i is a homomorphic image of $R/J(R)$. In view of Lemma 2.1, R_i be an abelian exchange ring, and that R_i is strongly π -clean by an argument in [11, Examples]. As every abelian exchange primitive ring is local, R_i is local. Therefore, R_i is potent from Lemma 2.6. This shows that $R/J(R)$ is potent, as desired.

Conversely, assume that (1) – (3) hold. By hypothesis, $S := R/J(R)$ is potent. Let $a \in S$. Then $a^m = a$ for some $m \geq 2$. Thus, $a^{m-1} \in S$ is an idempotent. Hence, $a^{m-1} = (1 - a^{m-1}) + (2a^{m-1} - 1)$, where $1 - a^{m-1} \in S$ is an idempotent and $2a^{m-1} - 1 = (2a^{m-1} - 1)^{-1} \in U(S)$. If there exist an idempotent $f \in S$ and a unit $u \in R$ such that $a^{m-1} = f + u$. As R is abelian, it is easy to verify that $(a^{m-1} + f - 1)(a^{m-1} - f)^2 = 0$, and so $f = 1 - a^{m-1}$; hence, $R/J(R)$ is strongly π -clean. Therefore we complete the proof by Theorem 2.2. \square

Theorem 2.8. *Let R be a ring. Then the following are equivalent:*

- (1) R is uniquely π -clean.
- (2) For any $a \in R$, there exists an $m \in \mathbb{N}$ and a central idempotent $e \in R$ such that $a^m - e \in J(R)$.

Proof. (1) \Rightarrow (2) In view of Lemma 2.7, $R/J(R)$ is potent. For any $a \in R$, $\bar{a} \in R/J(R)$ is potent, and so $\bar{a}^m \in R/J(R)$ is an idempotent for some $m \in \mathbb{N}$. By using Lemma 2.7 again, we can find a central idempotent $e \in R$ such that $\bar{a}^m = \bar{e}$, and so $a^m - e \in J(R)$.

(2) \Rightarrow (1) If $e \in R$ is an idempotent, then we have a central idempotent $f \in R$ such that $e - f \in J(R)$. As $(e - f)^3 = e - f$, we deduce that $e = f$; hence, every idempotent in R is central. If $e - e^2 \in J(R)$, then we can find a central idempotent $f \in R$ such that $e^m - f \in J(R)$ for some $m \in \mathbb{N}$. As $e - e^2 \in J(R)$, if $m \geq 3$, we see that $e - e^m = (e - e^2) + (e - e^2)e + \cdots + (e - e^2)e^{m-2} \in J(R)$. Thus $e - f \in J(R)$, and then idempotents lift modulo $J(R)$.

For any $a \in R$, there exist $m \in \mathbb{N}$ such that $a^m - e \in J(R)$ for a central idempotent. Hence, $\bar{a}^m = \bar{e}$ in $R/J(R)$. Thus, $S := R/J(R)$ is periodic. Thus, S is an abelian exchange ring. If $x^2 = 0$ and $x \neq 0$ in S , then $x \notin J(S)$. For any $r \in R$, there exists some $g \in R$ such that $1 - g \in R(1 - xr)$. Write $g = crx$ for a $c \in S$. Then $g = crgx = (cr)^2 x^2 = 0$, and so $1 - xr \in R$ is left invertible. As R is abelian, it is easy to check that $1 - xr \in U(R)$. This shows that $x \in J(S)$; hence, $x = 0$. This gives a contradiction. Therefore S is reduced.

Let $a \in R$, there exist $m, n (m > n)$ such that $\bar{a}^m = \bar{a}^n$ in S . Choose $k = n(m - n)$. It is easy to verify that $p = \bar{a}^{k+1}$ is potent and $w = \bar{a} - \bar{a}^{k+1} \in N(S)$. Further, $\bar{a} = p + w = p$ is potent, and so S is potent. Therefore complete the proof by Lemma 2.7. \square

Corollary 2.9. *Let R be a ring. Then R is uniquely clean if and only if*

- (1) R is uniquely π -clean;
- (2) $J(R) = \{x \in R \mid x - 1 \in U(R)\}$.

Proof. Obviously, $J(R) \subseteq \{x \in R \mid 1 - x \in U(R)\}$. Suppose that $1 - x \in U(R)$. Then we have an idempotent $e \in R$ and an element $u \in J(R)$ such that $x = e + u$ and $ex = xe$ by [11, Theorem 20]. Thus, $1 - e = (1 - x) + u \in U(R)$, and so $1 - e = 1$. This implies that $e = 0$; whence, $x = u \in J(R)$. Therefore $J(R) = \{x \in R \mid 1 - x \in U(R)\}$.

Conversely, assume that (1) and (2) hold. In view of Lemma 2.7, $R/J(R)$ is potent. It follows from $J(R) = \{x \in R \mid x - 1 \in U(R)\}$ that $U(R/J(R)) = \{\bar{1}\}$. Write $p = p^n (n \geq 2)$ in $R/J(R)$. Then $(1 - p^{n-1} + p)^{-1} = 1 - p^{n-1} + p^{n-2}$. Hence, $p = p^{n-1}$, and so $p^2 = p^n = p$. This implies that $R/J(R)$ is Boolean. Therefore we complete the proof by Lemma 2.1 and [11, Theorem 20]. \square

Theorem 2.10. *Let R be a ring. Then R is uniquely π -clean if and only if*

- (1) For any $a \in R$, there exists an $m \in \mathbb{N}$ and a unique $e \in R$ such that $a^m - e \in J(R)$.
- (2) $J(R) = \{x \in R \mid x^m - 1 \in U(R) \text{ for all } m \in \mathbb{N}\}$.

Proof. Suppose that R is uniquely π -clean. Let $a \in R$. In view of Theorem 2.8, there exists an $m \in \mathbb{N}$ and a central idempotent $g \in R$ such that $a^m - g \in J(R)$. If there exists an idempotent $f \in R$ such that $a^m - f \in J(R)$, then $g - f = (a^m - f) - (a^m - g) \in J(R)$. Clearly, $(g - f)^3 = g - f$, and so $(g - f)(1 - (g - f)^2) = 0$. Thus, $g = f$, i.e., the uniqueness is verified.

Clearly, $J(R) \subseteq \{x \in R \mid x^m - 1 \in U(R) \text{ for all } m \in \mathbb{N}\}$. If $x \notin J(R)$, then $0 \neq xR \not\subseteq J(R)$. In view of Lemma 2.1, R is an exchange ring, and so there exists an idempotent

$0 \neq e \in xR$. Write $e = xr$ for a $r \in R$. Choose $a = exe + 1 - e$. Then we can find some $m \in \mathbb{N}$ such that $a^m \in R$ is uniquely clean. In addition, R is abelian by Lemma 2.1. Obviously, $a^m = 0 + (ex^m e + 1 - e) = e + (e(x^m - 1)e + 1 - e)$. If $x^m - 1 \in U(R)$, then $0 = e$, a contradiction. This implies that $x^m - 1 \notin U(R)$. That is, $x \notin \{x \in R \mid x^m - 1 \in U(R) \text{ for all } m \in \mathbb{N}\}$. Therefore $\{x \in R \mid x^m - 1 \in U(R) \text{ for all } m \in \mathbb{N}\} \subseteq J(R)$, as required. \square

Conversely, assume that (1) and (2) hold. Let $x \in N(R)$. Then $x^m - 1 \in U(R)$ for all $m \in \mathbb{N}$. By hypothesis, we get $x \in J(R)$. Therefore, every nilpotent element in R is contained in $J(R)$. Let $e \in R$ be an idempotent, and let $r \in R$. Then $e + er(1 - e) \in R$ is an idempotent. Hence, there exists a unique $f \in R$ such that $(e + er(1 - e)) - f \in J(R)$. By the preceding discussion, $(e + er(1 - e)) - e = er(1 - e) \in J(R)$. The uniqueness forces $e = f$. But $(e + er(1 - e)) - (e + er(1 - e)) \in J(R)$, and so $e + er(1 - e) = f = e$. This shows that $er = ere$. Likewise, $re = ere$. That is, $er = re$, and then R is abelian. For any $a \in R$, there exists an $m \in \mathbb{N}$ and a unique $e \in R$ such that $w := a^m - e \in J(R)$. Then $a^m = (1 - e) + (2e - 1 + w)$. As $(2e - 1)^2 = 1$, we see that $2e - 1 + w \in U(R)$. If there exists an idempotent $f \in R$ such that $a^m - f \in U(R)$, then $e - f = (a^m - f) - (a^m - e) \in U(R)$. One easily checks that $(e + f - 1)(e - f)^2 = 0$, and therefore $e + f - 1 = 0$. Thus, $f = 1 - e$, hence the result. \square

Corollary 2.11. *Let R be a ring. Then R is uniquely π -clean if and only if*

- (1) *For any $a \in R$, there exists an $m \in \mathbb{N}$ and a unique $e \in R$ such that $a^m - e \in J(R)$.*
- (2) *$N(R) \subseteq J(R)$.*

Proof. Suppose that R is uniquely π -clean. (1) is obvious by Theorem 2.10. Let $a \in N(R)$. Then $1 - a^m \in U(R)$ for all $m \in \mathbb{N}$. It follows by Theorem 2.10 that $a \in J(R)$. Therefore $N(R) \subseteq J(R)$.

Conversely, assume that (1) and (2) hold. Let $e \in R$, and let $x \in R$. Then $ex(1 - e) \in J(R)$. By hypothesis, we have some $m \in \mathbb{N}$ such that the expressions $(e + ex(1 - e))^m = (e + ex(1 - e)) + 0 = e + ex(1 - e)$ are unique. This implies that $ex(1 - e) = 0$, and so $ex = exe$. Likewise, $xe = exe$. Therefore R is abelian. This yields the result by Theorem 2.8. \square

Corollary 2.12. *Let R be a local ring. Then the following are equivalent:*

- (1) *R is uniquely π -clean.*
- (2) *$U(R) = \{x \in R \mid \exists m \in \mathbb{N} \text{ such that } x^m - 1 \in J(R)\}$.*
- (3) *$J(R) = \{x \in R \mid x^m - 1 \in U(R) \text{ for all } m \in \mathbb{N}\}$.*

Proof. (1) \Rightarrow (3) is clear from Theorem 2.10.

(3) \Rightarrow (2) Obviously, $\{x \in R \mid \exists m \in \mathbb{N} \text{ such that } x^m - 1 \in J(R)\} \subseteq U(R)$. For any $x \in U(R)$, $x \notin J(R)$. By hypothesis, there exists some $m \in \mathbb{N}$ such that $x^m - 1 \notin U(R)$. As R is local, $x^m - 1 \in J(R)$. This implies that $U(R) \subseteq \{x \in R \mid \exists m \in \mathbb{N} \text{ such that } x^m - 1 \in J(R)\}$, as required.

(2) \Rightarrow (1) For any $x \in R$, we see that either $x \in J(R)$ or $x \in U(R)$. This implies that $\bar{x} = \bar{0}$ or $\bar{x} = \bar{1}$ in $R/J(R)$. Thus $R/J(R)$ is potent. In light of Lemma 2.7, R is uniquely π -clean. \square

3. FACTORS OF PRIME IDEALS

The aim of this section is to characterize uniquely π -clean rings by means of prime ideals contains the Jacobson radicals. We use $J\text{-spec}(R)$ to denote the set $\{P \in \text{Spec}(R) \mid J(R) \subseteq P\}$. Obviously, every maximal ideal is contained in $J\text{-spec}(R)$. Set

$$J^*(R) = \bigcap \{P \mid P \text{ is a maximal ideal of } R\}.$$

We will see that $J(R) \subseteq J^*(R)$. In general, they are not the same. For instance, $J(R) = 0$ and $J^*(R) = \{x \in R \mid \dim_F(xV) < \infty\}$, where $R = \text{End}_F(V)$ and V is an infinite-dimensional vector space over a field F . Furthermore, we characterize uniquely π -clean ring R by means of the radical-like ideal $J^*(R)$.

Lemma 3.1. [6, Corollary 2.8] *Let R be a commutative ring. Then the following are equivalent:*

- (1) R is strongly π -regular.
- (2) R is an exchange ring in which every prime ideal of R is maximal.

Lemma 3.2. *Let R be an abelian exchange ring, and let $x \in R$. Then $RxR = R$ if and only if $x \in U(R)$.*

Proof. If $x \in U(R)$, then $RxR = R$. Conversely, assume that $RxR = R$. As in the proof of [3, Proposition 17.1.9], there exists an idempotent $e \in R$ such that $e \in xR$ such that $ReR = R$. This implies that $e = 1$. Write $xy = 1$. Then $yx = y(xy)x = (yx)^2$. Hence, $yx = y(yx)x$. Therefore $1 = x(yx)y = xy(yx)xy = yx$, and so $x \in U(R)$. This completes the proof. \square

Theorem 3.3. *Let R be a ring. Then R is strongly π -clean if and only if*

- (1) R is abelian;
- (2) Every idempotent lifts modulo $J(R)$;
- (3) R/P is torsion for all $P \in J\text{-spec}(R)$.

Proof. Suppose R is strongly π -clean. In view of Lemma 2.1 and Lemma 2.7, R is an abelian exchange ring, and $R/J(R)$ is potent. Let $P \in J\text{-spec}(R)$. Then $R/J(R)/P/J(R) \cong R/P$ is prime; hence, $P/J(R)$ is a prime ideal of $R/J(R)$. As every potent ring is commutative, $R/J(R)$ is a commutative π -regular ring. It follows from Lemma 3.1 that $P/J(R)$ is a maximal ideal of $R/J(R)$. We infer that P is a maximal ideal of R .

Clearly, $\overline{R} := R/P$ is an abelian exchange ring. Since P is maximal, R/P is simple. For any $0 \neq x \in \overline{R}$, we have $\overline{R}x\overline{R} = \overline{R}$. By virtue of Lemma 3.2, $x \in U(R/P)$. Hence, R/P is a division ring. On the other hand, $R/P \cong R/J(R)/P/J(R)$ is potent. Thus, we have some $m \in \mathbb{N}$ such that $x^{m+1} = x$, and so $x^m = 1$. This implies that R/P is torsion, as required.

Conversely, assume that (1) – (3) hold. Assume that R is not strongly π -clean. Set $S = R/J(R)$. In view of Theorem 2.8, S is not periodic. By using Herstein's Theorem, there exists some $a \in S$ such that $a^m \neq a^{m+1}f(a)$ for any $m \in \mathbb{N}$ and any $f(x) \in \mathbb{Z}[x]$. Let $\Omega = \{I \triangleleft S \mid \overline{a}^m \neq \overline{a}^{m+1}f(\overline{a}) \text{ in } S/I \text{ for any } m \in \mathbb{N} \text{ and any } f(x) \in \mathbb{Z}[x]\}$. Then Ω is a nonempty inductive. By using Zorn's Lemma, there exists an ideal Q of S which is maximal in Ω . If Q is not prime, then there exist two ideals K and L of R such that $K, L \not\subseteq Q$ and $KL \subseteq Q$. By the maximality of Q , we can find some $s, t \in \mathbb{N}$ and some $f(x), g(x) \in \mathbb{Z}[x]$ such that $\overline{a}^s = \overline{a}^{s+1}f(\overline{a})$ in $R/(K+Q)$ and $\overline{a}^t = \overline{a}^{t+1}g(\overline{a})$ in $R/(L+Q)$. Thus, $a^s - a^{s+1}f(a) \in K+Q$ and $a^t - a^{t+1}g(a) \in L+Q$, and so $(a^s - a^{s+1}f(a))(a^t -$

$a^{t+1}g(a) \in (K+Q)(L+Q) \subseteq KL+Q \subseteq Q$. In S/Q , we have $\bar{a}^{s+t} = \bar{a}^{s+t+1}h(\bar{a})$ for some $h(x) \in \mathbb{Z}[x]$. This contradicts the choice of Q . Hence, $Q \in J\text{-spec}(R)$. By hypothesis, R/Q is torsion, and so R/Q is periodic, which is imposable. Therefore R is strongly π -clean. \square

Corollary 3.4. *A ring R is uniquely clean if and only if*

- (1) R is uniquely π -clean.
- (2) $R/M \cong \mathbb{Z}_2$ for all maximal ideals M of R .

Proof. Suppose R is uniquely clean. Then R is uniquely π -clean. (2) is proved by [2, Theorem 2.1].

Conversely, assume that (1) and (2) hold. For all maximal ideals M of R , $1_{R/M}$ is not the sum of two units in R/M . In view of Lemma 2.1, R is an abelian exchange ring, and so it is clean. Let $x \in R$. Write $x = e_1 + u_1 = e_1 + u_2$, $e_1 = e_1^2$, $e_2 = e_2^2$ and $u_1, u_2 \in U(R)$. If $R(1 - e_2(1 - e_1))R \neq R$, then there exists a maximal ideal M of R such that $R(1 - e_2(1 - e_1))R \subseteq M$. Clearly, $J(R) \subseteq M$. Hence, $\bar{x} = \bar{e}_1 + \bar{u}_1 = \bar{e}_2 + \bar{u}_2$ in R/M . By Theorem 3.3, R/M is a division ring. This implies that \bar{e}_i are $\bar{0}$ or $\bar{1}$. If $\bar{e}_1 \neq \bar{e}_2$, then $1_{R/M}$ is the sum of two units, a contradiction. Therefore we get $e_1 - e_2 \in M$. This infers that $e_2(1 - e_1) = (e_1 - e_2)(e_1 - 1) \in M$, and so $1 = e_2(1 - e_1) + (1 - e_2(1 - e_1)) \in M$, a contradiction. As a result, $R(1 - e_2(1 - e_1))R = R$. As $e_2(1 - e_1) \in R$ is an idempotent, we get $e_2(1 - e_1) = 0$, and so $e_2 = e_2e_1$. Likewise, $e_1 = e_1e_2$. Consequently, $e_1 = e_2$, and then $u_1 = u_2$. Therefore R is uniquely clean. \square

Let $S(R)$ be the nonempty set of all ideals of a ring R generated by central idempotents. By Zorn's Lemma, $S(R)$ contains maximal elements. As usual, we say that R/P is a Pierce stalk if P is a maximal element of the set $S(R)$, and that P is a Pierce ideal. Let $\text{Pier}(R)$ be the set of all Pierce ideals of R .

Proposition 3.5. *Every uniquely π -clean ring is the subdirect product of rings R_i , where each $R_i/J(R_i)$ is torsion.*

Proof. Let R be a uniquely π -clean ring. In view of [9, Remark 11.2], $\bigcap \{P \mid P \in \text{Pier}(R)\} = 0$. Let $\varphi_P : R \rightarrow R/P$ be the natural epimorphism. Then $\bigcap_{P \in \text{Pier}(R)} \ker \varphi_P = \bigcap_{P \in \text{Pier}(R)} P = 0$. Hence, R is the subdirect product of all R/P , where $P \in \text{Pier}(R)$. In view of Lemma 2.1, R is an abelian exchange ring. Let $P \in \text{Pier}(R)$. Then R/P is an exchange ring. As R is indecomposable, we see that R/P is a local ring. By an argument in [11], R/P is uniquely π -clean, and so $R/P/J(R/P)$ is potent from Lemma 2.7, as needed. \square

Lemma 3.6. *Let R be an abelian exchange ring. Then $J^*(R) = J(R)$.*

Proof. Let M be a maximal ideal of R . If $J(R) \not\subseteq M$, then $J(R) + M = R$. Write $x + y = 1$ with $x \in J(R)$, $y \in M$. Then $y = 1 - x \in U(R)$, an absurd. Hence, $J(R) \subseteq M$. This implies that $J(R) \subseteq J^*(R)$. Let $x \in J^*(R)$, and let $r \in R$. If $R(1 - xr)R \neq R$, then we can find a maximal ideal M of R such that $R(1 - xr)R \subseteq M$, and so $1 - xr \in M$. It follows that $1 = xr + (1 - xr) \in M$, which is imposable. Therefore $R(1 - xr)R = R$. In light of Lemma 3.2, $1 - xr \in U(R)$, and then $x \in J(R)$. This completes the proof. \square

Theorem 3.7. *Let R be a ring. Then R is uniquely π -clean if and only if*

- (1) R is an exchange ring;
- (2) $R/J^*(R)$ is potent and every idempotent uniquely lifts modulo $J^*(R)$.

Proof. Suppose R is uniquely π -clean. Then R is an abelian exchange ring by Lemma 2.1. In view of Lemma 3.6, $J^*(R) = J(R)$. It follows from Lemma 2.7 that $R/J^*(R)$ is potent. Let $e - e^2 \in J(R)$. Then we can find an idempotent $f \in R$ such that $e - f \in J(R)$. Since $(e - f)^2(1 - (e - f)) = 0$, we get $e = f$, as desired.

Conversely, assume that (1) and (2) hold. Let $e \in R$ be an idempotent, and let $r \in R$. Then $er(1 - e) \in R/J^*(R)$ is potent. This implies that $er(1 - e) = \bar{0}$, and so $er(1 - e) \in J^*(R)$. Since $e - e, e - (e + er(1 - e)) \in J^*(R)$, by the uniqueness, we get $e = e + er(1 - e)$, and so $er = ere$. Likewise, $re = ere$; hence that $er = re$. Thus, R is abelian. In light of Lemma 3.6, $J^*(R) = J(R)$. Therefore we complete the proof, in terms of Lemma 2.7. \square

Corollary 3.8. *Let R be a ring which have finitely many maximal ideals. Then R is uniquely π -clean if and only if*

- (1) R is an exchange ring;
- (2) $R/J^*(R)$ is the direct sum of finitely many torsion rings and every idempotent uniquely lifts modulo $J^*(R)$.

Proof. (1) \Rightarrow (2) Let M be a maximal ideal of R . As in the proof of Lemma 3.6, we see that $J(R) \subseteq M$. This shows that $M \in J\text{-spec}(R)$. Therefore R/M is torsion by Theorem 3.3. Since R has finitely many maximal ideals M_1, \dots, M_n , we see that $R/J^*(R) \cong R/M_1 \oplus \dots \oplus R/M_n$. Therefore $R/J^*(R)$ is the direct sum of finitely many torsion rings.

(2) \Rightarrow (1) As every torsion ring is potent, we see that $R/J^*(R)$ is potent. Therefore we complete the proof, by Theorem 3.7. \square

Theorem 3.9. *Let R be a ring. Then R is uniquely π -clean if and only if*

- (1) For any $a \in R$, there exists an $m \in \mathbb{N}$ and a unique $e \in R$ such that $a^m - e \in J^*(R)$.
- (2) $J^*(R) = \{x \in R \mid x^m - 1 \in U(R) \text{ for all } m \in \mathbb{N}\}$.

Proof. One direction is obvious by Lemma 3.6 and Theorem 2.10.

Conversely, assume that (1) and (2) hold. Let $x \in N(R)$. Then $x^m - 1 \in U(R)$ for all $m \in \mathbb{N}$. By hypothesis, we have $x \in J^*(R)$, and so $N(R) \subseteq J^*(R)$. Let $e \in R$ be an idempotent, and let $r \in R$. Then $e + er(1 - e) + 0 = e + er(1 - e)$ with $0, er(1 - e) \in J^*(R)$. By the uniqueness, we get $er = ere$. Similarly, we have $re = ere$. That is, $er = re$. We infer that R is abelian. For any $a \in R$, there exists an $m \in \mathbb{N}$ and a unique $e \in R$ such that $w := a^m - e \in J^*(R)$. Then $a^m = (1 - e) + (2e - 1 + w)$. But $2e - 1 + w = (1 - 2e)((1 - 2e)w - 1) \in U(R)$, by (2). If there exists an idempotent $f \in R$ such that $a^m - f \in U(R)$, then $e - f = (a^m - f) - (a^m - e) = (a^m - f)(1 - (a^m - f)^{-1}(a^m - e)) \in U(R)$. It follows from $(e + f - 1)(e - f)^2 = 0$ that $f = 1 - e$, and we are through. \square

Let $P(R)$ be the intersection of all prime ideals of R , i.e., $P(R)$ is the prime radical of R . As is well known, $P(R)$ is the intersection of all minimal prime ideals of R .

Corollary 3.10. *Let R be a uniquely π -clean in which every prime ideal is maximal. Then*

$$P(R) = \{x \in R \mid x^m - 1 \in U(R) \text{ for all } m \in \mathbb{N}\}.$$

Proof. As every maximal ideal is prime, we deduce that $J^*(R) = P(R)$, and therefore we complete the proof by Theorem 3.9. \square

4. CERTAIN CLASSES

In this section we investigate certain classes of uniquely π -clean rings. So as to construct more examples of uniquely clean rings, we recall the concept of ideal-extensions. Let R be a ring with an identity and S be a ring (not necessary unitary), and let S be a R - R -bimodule in which $(s_1 s_2)r = s_1(s_2 r)$, $r(s_1 s_2) = (r s_1)s_2$ and $(s_1 r)s_2 = s_1(rs_2)$ for all $s_1, s_2 \in S, r \in R$. The ideal extension $I(R; S)$ is defined to be the additive abelian group $R \oplus S$ with multiplication $(r_1, s_1)(r_2, s_2) = (r_1 r_2, s_1 s_2 + r_1 s_2 + s_1 r_2)$ (see [4] and [10]). We start this section by examining when an ideal extension is uniquely π -clean.

Theorem 4.1. *The ideal-extension $I(R; S)$ is uniquely π -clean and S is idempotent-free if and only if*

- (1) R is uniquely π -clean;
- (2) If $e = e^2 \in R$, then $es = se$ for all $s \in S$;
- (3) If $s \in S$, then there exists some $s' \in S$ such that $ss' = s's$ and $s + s' + ss' = 0$.

Proof. Assume that (1)–(3) hold. Let $e \in S$ be an idempotent. Then $(-e) + s' + (-e)s' = 0$ for some $s' \in S$. Hence, $(1 - e)(1 + s') = 1$, and so $e = 0$. That is, S is idempotent-free. Let $(a, s) \in I(R; S)$. Then $a \in R$ is uniquely π -clean. Thus, we have some $n \in \mathbb{N}$ such that $a^n \in R$ is uniquely clean. Write $a^n = e + u, e = e^2 \in R, u \in U(R)$. Hence, $(a, s)^n = (a^n, x) = (e, 0) + (u, x)$ for some $x \in S$. Clearly, $(e, 0)^2 = (e, 0)$ and $(u, x)^{-1} = (u^{-1}, zu^{-1})$ for a $z \in S$. Write $(a, s)^n = (f, y) + (v, w), (f, y)^2 = (f, y)$ and $(v, w) \in U(I(R; S))$. Then $f = f^2 \in R, y = 0$ and $v \in U(R)$. Further, $a^n = f + v$ and $x = w$. This implies that $f = e, v = u$, and so $(f, y) = (e, 0), (v, w) = (u, x)$. As a result, $(a, s) \in I(R; S)$ is uniquely π -clean, and so $I(R; S)$ is uniquely π -clean.

Assume that $I(R; S)$ is uniquely π -clean and S is idempotent-free. Then R is uniquely π -clean. Let $e = e^2 \in R$ and $s \in S$. In view of Lemma 2.1, $(e, 0) = (e, 0)^2 \in I(R; S)$ is central. Hence, $(e, 0)(0, s) = (0, s)(e, 0)$, and so $es = se$. For any $s \in S$, there exists some $n \in \mathbb{N}$ such that $(1, s)^n \in I(R; S)$ is uniquely clean. Write $(1, s)^n = (1, x) = (f, y) + (u, v)$ where $x \in S, (f, y) \in I(R; S)$ is an idempotent and $(u, v) \in I(R; S)$ is a unit. Clearly, $f = 0$, and so $y = 0$. This implies that $x = y + v = v$; hence, $(1, x) \in I(R; S)$ is a unit. Further, $(1, s) \in I(R; S)$ is a unit. Write $(1, s)^{-1} = (1, s')$ for a $s' \in S$. Then $ss' = s's$ and $s + s' + ss' = 0$, hence the result. \square

Corollary 4.2. *Let R be uniquely π -clean. Then $S = \{(a_{ij}) \in T_n(R) \mid a_{11} = \cdots = a_{nn}\}$ is uniquely π -clean.*

Proof. Let $T = \{(a_{ij}) \in T_n(R) \mid a_{11} = \cdots = a_{nn} = 0\}$. Then $S \cong I(R; T)$. Then the result follows by Theorem 4.1. \square

A ring R is called *potently J -clean* if for any $a \in R$ there exists a potent $p \in R$ such that $a - p \in J(R)$. We shall show that such rings form a subclass of uniquely π -clean rings.

Lemma 4.3. *Every potently J -clean ring is an exchange ring.*

Proof. Let R be a potently J -clean ring. Then $R/J(R)$ is potent, and so it is an exchange ring. Let $\bar{e} \in R/J(R)$ be an idempotent. Then we have a potent $p \in R$ such that $w := e - p \in J(R)$. Write $p = p^n$ for some $n \geq 2$. Then $p^{n-1} \in R$ is an idempotent. Moreover, $e = p + w$, and so $e^{n-1} = p^{n-1} + v$ for some $v \in J(R)$. But $e - e^{n-1} \in J(R)$. Hence, $e - p^{n-1} = (e - e^{n-1}) + (e^{n-1} - p^{n-1}) \in J(R)$. So idempotents can be lifted modulo $J(R)$. In light of [9, Theorem 29.2], R is an exchange ring. \square

Theorem 4.4. *Every abelian potentially J -clean ring is uniquely π -clean.*

Proof. Let R be an abelian potentially J -clean ring. Then R is an exchange ring by Lemma 4.3. Thus, every idempotent in R lifts modulo $J(R)$. For any $a \in R$, there exists a potent $p \in R$ such that $a - p \in J(R)$. This implies that $\bar{a} \in R/J(R)$ is potent, and so $R/J(R)$ is potent. According to Lemma 2.7, R is uniquely π -clean. \square

Corollary 4.5. *Let R be abelian. If for any sequence of elements $\{a_i\} \subseteq R$ there exists a $k \in \mathbb{N}$ and $n_1, \dots, n_k \geq 2$ such that $(a_1 - a_1^{n_1}) \cdots (a_k - a_k^{n_k}) = 0$, then R is uniquely π -clean.*

Proof. For any $a \in R$, we have a $k \in \mathbb{N}$ and $n_1, \dots, n_k \geq 2$ such that $(a - a^{n_1}) \cdots (a - a^{n_k}) = 0$. This implies that $a^k = a^{k+1}f(a)$ for some $f(t) \in \mathbb{Z}[t]$. By Herstein's Theorem, R is periodic. Therefore every element in R is the sum of a potent element and a nilpotent element.

Clearly, $R/J(R)$ is isomorphic to a subdirect product of some primitive rings R_i . Case 1. There exists a subring S_i of R_i which admits an epimorphism $\phi_i : S_i \rightarrow M_2(D_i)$ where D_i is a division ring. Case 2. $R_i \cong M_{m_i}(D_i)$ for a division ring D_i . Clearly, the hypothesis is inherited by all subrings, all homomorphic images and all corners of R , we claim that, for any sequence of elements $\{a_i\} \subseteq M_2(D_i)$ there exists $s \in \mathbb{N}$ and $m_1, \dots, m_s \geq 2$ such that $(a_1 - a_1^{m_1}) \cdots (a_s - a_s^{m_s}) = 0$. Choose $a_i = e_{12}$ if i is odd and $a_i = e_{21}$ if i is even. Then $(a_1 - a_1^{m_1})(a_2 - a_2^{m_2}) \cdots (a_s - a_s^{m_s}) = a_1 a_2 \cdots a_s \neq 0$, a contradiction. This forces $m_i = 1$ for all i . We infer that all R_i is reduced, and then so is $R/J(R)$. If $a \in N(R)$, we have some $n \in \mathbb{N}$ such that $a^n = 0$, and thus $\bar{a}^n = 0$ in $R/J(R)$. Hence, $\bar{a} \in J(R/J(R)) = 0$. This implies that $a \in J(R)$, and so $N(R) \subseteq J(R)$. Therefore R is potentially J -clean, hence the result by Theorem 4.4. \square

Recall that an element $a \in R$ is uniquely nil clean provided that there exists a unique idempotent $e \in R$ such that $a - e \in N(R)$ [2].

Lemma 4.6. *Let R be a ring. Then the following are equivalent:*

- (1) R is an abelian periodic ring.
- (2) For any $a \in R$, there exists some $m \in \mathbb{N}$ such that $a^m \in R$ is uniquely nil clean.

Proof. (1) \Rightarrow (2) Let $a \in R$. Since R is periodic, there exists some $m \in \mathbb{N}$ such that $a^m \in R$ is an idempotent. Write $a^m = e + w$ where $e = e^2 \in R$ and $w \in N(R)$. Then $a^m - e = w \in N(R)$. As R is abelian, we see that $(a^m - e)^3 = a^m - e$. Thus, $(a^m - e)(1 - (a^m - e)^2) = 1$, and so $a^m = e$, as required.

(2) \Rightarrow (1) Let $e \in R$ be an idempotent and $r \in R$. Choose $a = e + er(1 - e)$. Then we can find some $m \in \mathbb{N}$ such that $a^m \in R$ is uniquely nil clean. As $a = a^m = e + er(1 - e) = (e + er(1 - e)) + 0$, by the uniqueness, we get $er(1 - e) = 0$, and so $er = ere$. Likewise, $re = ere$, and so $er = re$. Therefore R is abelian. Let $a \in R$. Then there exists some $n \in \mathbb{N}$ such that $a^n = f + u$, where $f = f^2 \in R$ and $u \in N(R)$. Hence, $a^{2n} = f + v$ for a $v \in N(R)$ and $uv = vu$. This shows that $a^n - a^{2n} = u - v \in N(R)$. Thus, we have a $k \in \mathbb{N}$ such that $a^{nk} = a^{nk+1}f(a)$ for some $f(t) \in \mathbb{Z}[t]$. In light of Herstein's Theorem, R is periodic. \square

Theorem 4.7. *Let R be a ring. Then the following are equivalent:*

- (1) R is uniquely π -clean and $J(R)$ is nil.
- (2) R is an abelian periodic ring.

- (3) For any $a \in R$, there exists some $m \in \mathbb{N}$ and a unique idempotent $e \in R$ such that $a^m - e \in P(R)$.

Proof. (1) \Rightarrow (2) In view of Lemma 2.7, $R/J(R)$ is potent. Let $a \in R$. Then $\bar{a} = \overline{a^m}$ ($m \geq 2$), and so \bar{a}^{m-1} is an idempotent. As $J(R)$ is nil, every idempotent lifts modulo $J(R)$. Hence, we can find an idempotent $e \in R$ such that $a^{m-1} = e + w$, where $w \in J(R)$ is nilpotent. Write $a^{m-1} = f + v$ with $f = f^2 \in R$ and $v \in N(R)$. In view of Lemma 2.1, R is abelian. Then $e - f = v - w \in N(R)$, as $vw = wv$. It follows from $e - f = (e - f)^3$ that $e = f$. Thus, proving (2) by Lemma 4.6.

(2) \Rightarrow (3) For any $a \in R$, by Lemma 4.6, there exists some $m \in \mathbb{N}$ such that a^m is uniquely nil clean. Write $a^m = e + w$ with $e = e^2$ and $w \in N(R)$. In view of [1, Theorem 2], $N(R)$ forms an ideal of R . Therefore $N(R) = P(R)$, as required.

(3) \Rightarrow (1) Let $e \in R$ be an idempotent, and let $r \in R$. Then we have an idempotent $f \in R$ such that $er(1 - e) = f + w$ for a $w \in P(R)$. Hence, $1 - f = 1 - er(1 - e) + w = (1 - er(1 - e))(1 + (1 + er(1 - e))w) \in U(R)$. We infer that $f = 0$, and so $er(1 - e) = w \in P(R)$. But we have a unique expression $e + er(1 - e) = e + er(1 - e) + 0$ where $er(1 - e), 0 \in P(R)$. By the uniqueness, we get $e = e + er(1 - e)$, and so $er = ere$. Similarly, $re = ere$. Therefore $er = re$, i.e., R is abelian.

Let $x \in J(R)$. Write $x = h + v$ with $h = h^2 \in R, v \in P(R)$. Then $h = x - v \in J(R)$; hence that $h = 0$. It follows that $J(R) = P(R)$. Accordingly, for any $a \in R$, there exists some $m \in \mathbb{N}$ and a unique idempotent $e \in R$ such that $a^m - e \in J(R)$.

If $x \in N(R)$, then we have an idempotent $g \in R$ and a $u \in P(R)$ such that $x = g + u$, and so $g = x - u$. As R is abelian, we see that $xu = ux$, and then $g \in N(R)$. This shows that $g = 0$. Consequently, $x = u \in P(R) \subseteq J(R)$. We infer that $N(R) \subseteq J(R)$. In light of Corollary 2.11, we complete the proof. \square

As every finite ring is periodic, it follows from Theorem 4.7 that every finite commutative ring is uniquely π -clean, e.g., $\mathbb{Z}_n[\alpha] = \{a + b\alpha \mid a, b \in \mathbb{Z}_n, \alpha = -\frac{1}{2} + \frac{\sqrt{3}}{2}i, i^2 = -1\}$.

Corollary 4.8. *Let R be a ring. Then the following are equivalent:*

- (1) R is uniquely π -clean and $J(R)$ is nil.
- (2) For any $a \in R$, there exists some $m \in \mathbb{N}$ and a central idempotent $e \in R$ such that $a^m - e \in P(R)$.

Proof. (1) \Rightarrow (2) This is obvious, in terms of Theorem 4.7 and Lemma 2.1.

(2) \Rightarrow (1) For any $a \in R$, there exists some $m \in \mathbb{N}$ and a central idempotent $e \in R$ such that $a^m - e \in P(R)$. Write $a^m - f \in P(R)$ for an idempotent. Then $e - f = (a^m - f) - (a^m - e) \in P(R)$. As $(e - f)^3 = e - f$, we conclude that $e = f$, and we are through by Theorem 4.7. \square

Let $n \geq 2$ be a fixed integer. Following Yaqub, a ring R is said to be generalized n -like provided that for any $a, b \in R$, $(ab)^n - ab^n - a^n b + ab = 0$ ([7-8]).

Corollary 4.9. *Every generalized n -like ring is uniquely π -clean.*

Proof. Let $a \in R$. Then $a^{2n} - 2a^{n+1} + a^2 = 0$, and so $(a - a^n)^2 = 0$. Thus, $a - a^n \in N(R)$. Hence, $a^m = a^{m+1}f(a)$ for some $f(t) \in \mathbb{Z}[t]$. Accordingly, R is periodic by Herstein's Theorem.

Let $e, f \in R$. Then there exist some $m, n \geq 2$ such that

$$\begin{aligned} ((1 - e)f)^m e &= ((1 - e)fe)^m - (1 - e)fe + (1 - e)fe = 0; \\ ((1 - e)f)^n &= (1 - e)f + (1 - e)f - (1 - e)f = (1 - e)f. \end{aligned}$$

Reiterating in the last, we get $(1 - e)f = ((1 - e)f)^{n+m}$, and so $(1 - e)fe = 0$. Hence, $fe = ef e$. Likewise, $ef = ef e$. Therefore $ef = fe$. We infer that R is abelian.

Therefore we conclude that R is uniquely π -clean, in terms of Theorem 4.7. \square

Let $R = \left\{ \begin{pmatrix} x & y & z \\ 0 & x^2 & 0 \\ 0 & 0 & x \end{pmatrix} \mid x, y, z \in GF(4) \right\}$. It is easy to check that for each $a \in R$, $a^7 = a$ or $a^7 = a^2 = 0$. Therefore R is a generalized 7-like ring. By Corollary 4.9, R is uniquely π -clean which is a noncommutative periodic ring.

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